PERFORMANCE OF A FLOTATION COLUMN FUZZY CONTROLLER

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Abstract: The performance of a fuzzy controller to stabilize the operation of a flotation column is evaluated. Three key process variables are controlled by manipulation of the flow rates of the three main flow streams. The controller, which is based on a fuzzy logic inference system of Mamdani type with heuristically developed rules, works in real time and has the possibility of load rejection control as well as servo control of two controlled variables.

Key-Words: Flotation Column, Fuzzy Control, Mamdani Rules, Heuristic Knowledge, Real Time, Hybrid Controller IMACS/IEEE CSCC'99 Proceedings, Pages:6751-6756

1 Introduction

The column flotation process separates very fine solid particles based on physical and chemical properties of their surfaces. It is a continuous solid-solid separation process widely used in the concentration of low grade and finely disseminated ores, as well as, in recycling and solvent extraction.

Flotation columns are long vertical vessels that are continuously fed with a pulp, 15 to 40% solids by weight, of fine (100 to 10 μ m) solid particles to be separated (figure 1). The pulp is previously conditioned with the controlled addition of small quantities of specific chemical reagents to promote the selective formation of aggregates between solid particles of a given composition and air bubbles.





Air is continuously injected to the pulp through a sparger at the bottom of the column, giving rise to the

formation of a swarm of air bubbles. Particles previously made hydrophobic adhere, after collision, to the air bubbles which move upwards to the top of the column where they are recovered as the column overflow or floated product. Hydrophilic particles settle in the pulp which moves downwards to the bottom leaving the column as the underflow.

During normal operation two distinct zones are formed inside the column: collection zone where the hydrophobic particles are collected by the air bubbles and the froth zone constituted mainly by air (60-90%) and the collected particles [1].

A distintive feature of flotation column operation is the addition of fresh washing water through the top of the column to clean the froth zone by drainage of the hydrophilic particles entrained in the air bubbleshydrophobic particles aggregates.

The automatic control of the main process variables is mandatory to stable operation of the flotation column. The ultimate goal of the column flotation process control is to achieve the economic optimum combination of the desired mineral grade (purity) and recovery in the final product from a feed of varying composition.

Experience has shown that 3 process variables: collection zone height, air holdup (volumetric percentage of air) in the collection zone and bias water flow rate (net flow of washing water passing through the froth zone), are key parameters to the metallurgical column performance. However, these cannot be directly manipulated. Instead, washing water, air and underflow flow rates are variables that can be directly manipulated. The development of column flotation process controllers based on mathematical dynamic models is not yet possible due to the poor understanding of the process internal mechanisms, on the one hand, and to the time-varying non linear behaviour, on the other hand.

However, this process is controlled by skilled operators that, taking into account the measurements of some variables, are able to manipulate a few operating variables in order to guarantee the stable operation of the flotation column.

Fuzzy logic inference systems can be a solution to develop controllers of complex hard-to-model processes, whose behaviour can, nevertheless, be described by linguistic rules (for example, from operators experience) [2].

This paper describes briefly a fuzzy controller that aims the stable operation of a flotation column and presents the evaluation of its performance, in load rejection control and servo control, under different operational conditions.

2 Pilot Flotation Column Description. Controlled and Manipulated Variables

The pilot flotation column is a tube in acrylic of 80mm diameter by 3,2m height. The feed is introduced at about 1/3 of column height from the top and air is introduced some centimeters above the bottom end.

Controlled variables are the air holdup in the collection zone (ε_c), collection zon e height (H) and bias water flow rate (Q_B). These variables are not directly measurable. However, they can be estimated or inferred from other measured variables. ε_c and H are calculated from measurements of two pressure sensors mounted on the column wall. The value of Q_B is approximated by the difference between underflow and feed flow rates (corrected for H variation).

Manipulated variables are air (Q_A) , wash water (Q_W) and underflow (Q_U) flow rates. All the flow rates (including feed flow rate) are measured with different flowmeter types and their control is achieved by direct manipulation of variable speed pumps and control valves, using local PID controllers.

The work presented here considers only the two phase system, an air and water mixture. A constant frother concentration of 10ppm was used for froth stabilization.

3 Fuzzy Controller

The fuzzy controller is a *hybrid* controller working in an *emergence mode* (classical inference) when the operating conditions are considered to be abnormal and in *fuzzy mode*, when the control is achieved by fuzzy inference [3].

The conditions are considered to be *abnormal* when the collection zone height is too low or too high, i.e., when H is some centimeters above or bellow the set-point. In this case it is desirable to drive H as fast as possible to the neighborhood of its set-point. When an abnormal situation is detected, both underflow and washing water flowrates are manipulated under severe conditions.

Otherwise, the control is made under fuzzy mode, i.e., the manipulated variables are calculated by fuzzy inference. The controller, that works in real time, is a fuzzy logic inference system of Mamdani type with essentially heuristic-based rules.

In a previous study [4] the experimental tuning of the controller was performed. It has been shown how hard and time-consuming is the task of tuning a control system with so many interdependent parameters. Small variations of one parameter entails the need of changing other parameters and subsequent experimental evaluation.

Another important conclusion of that study was that the controlled system performance using a simple rule base with 11 rules was comparable to those achieved with the use of more complex rule bases. In fact, operators can drive the process based on only a few simple rules.

The fuzzy controller, after tuning, has the following main characteristics (see, for example, [5]):

- the controlled variables universes of discourse are functions of the respective set-points;

- the membership functions are sinusoidal mathematical functions, with numerical parameters heuristically determined and experimentally tuned;

- the rule base was heuristically developed. It has 11 rules (Table 1);

- it has a max-prod inference motor;

- defuzzification is made by the center of gravity method.

4 Experimental Design and Evaluation

Due to the inexistence of mathematical dynamic models that can be used in simulation, an extensive experimental study was undertaken to evaluate the performance of the controlled system (see table 2).

 Table 1 - Rule base used by the fuzzy controller

If H low then $Q_U low$; If H medium and $Q_B low$ then $Q_U high$; If H medium and Q_B medium then Q_U medium; If H medium and $Q_B high$ then $Q_U low$; If H high then $Q_U high$;

If H low then Q_w high; If H medium then Q_w medium; If H high then Q_w low;

If $\varepsilon_c \ low$ then $Q_A \ high$; If $\varepsilon_c \ medium$ then $Q_A \ medium$; If $\varepsilon_c \ high$ then $Q_A \ low$;

Experimental design included 9 tests. In each test, after achieving steady state operation, one variable was disturbed according with the scheme illustrated in Figure 2. The following disturbances were generated:

- load disturbance, i.e., disturbance of an independent variable that is not manipulated by the fuzzy controller. Feed flowrate (Q_F) was the independent variable chosen (tests 3, 4 and 5).

- controlled variables set-point disturbance (servo control). Only the set points of H (H^{SP}) and $Q_B (Q_B^{SP})$ were modified. Modification of the air holdup set-point was not considered because the servo control of this variable is not achievable by manipulation of one or more of the manipulated variables, unless a modification of the frother concentration is made. Due to the long time delay of the air holdup response to the changes of frother concentration, that was not considered. The frother concentration was kept constant and the control of ε_c intends only the rejection of load disturbances or others variable set point modifications.



Fig. 2 - Sequence of disturbances generated during tests.

Table 2 - Experimental design

Test	Initia Controlle	Disturbed		
	H (cm)	$Q_{B}\left(l/h\right)$	$\mathbf{Q}_{\mathrm{F}}\left(\mathbf{l}/\mathbf{h} ight)$	Variables
1	25	10	100	H _{Sb}
2	25	10	100	$Q_{\rm B}^{\ \rm SP}$
3	25	10	100	$Q_{\rm F}$
4	15	10	100	$Q_{\rm F}$
5	35	10	100	$Q_{\rm F}$
6	35	10	100	$Q_{\rm B}^{\ \rm SP}$
7	15	10	100	$Q_{\rm B}^{\rm SP}$
8	25	10	80	H _{Sb}
9	25	7	100	H ^{SP}

The evaluation of the controlled system performance is a compromise between the speed of response, stability and accuracy. Depending on the weight that can be given to each one of these criteria, a different controller can be obtained. Three performance parameters or indices were considered for evaluation:

- settling time, defined as the time, after the disturbance, the controlled variable takes to reach a new steady state value. This parameter is a measure of the speed of response. In each test, four step changes were performed, therefore, four settling times were determined and an arithmetic average, ST, was calculated.

- steady state error is the average deviation of the controlled variable from its set-point. In each test, five steady state errors were determined and an arithmetic average, SSE, was computed.

- standard deviation, σ , defined as follows

$$\sigma = \sqrt{\frac{\sum e^{\theta}(t)}{N-1}}$$
(1)

where e(t) is the deviation of the variable from its setpoint and N is the number of sampling intervals during the test. This parameter can be viewed as a measure of the stability.

5 Results

Table 3 shows the maximum values of the performance parameters ST, SSE and σ calculated for the tests

performed.

	SSE		ST (s)		σ	
Variable Disturbed	H (cm)	Q _B (l/h)	Н	Q _B	H (cm)	Q _B (l/h)
Q _F	0.9	0.5	-	-	1.4	3.9
H ^{SP}	0.4	1.0	52	-	2.3	7.6
	1.1	0.9	-	14	1.4	2.6

Table 3 - Maximum values of performance parameters

5.1 Load Disturbance

The responses of H and Q_B to Q_F disturbance, presented in figures 3 and 4, show that these two controlled variables are not significantly affected by the disturbance of the feed flow rate. The maximum average steady state errors obtained were 0.9cm for H and 0.51/h for Q_B (both less than the estimation error of these variables). The maximum standard deviations are 1.4cm for H and 3.9 1/h for Q_B . Figures 5 and 6 show the manipulated variables responses.

5.2 Set-point Disturbances

Figures 7 and 8 show response of H and Q_B to H^{SP} disturbance. In all tests performed the average SSE was lower than 0.4cm for H and 11/h for Q_B . The average ST was less than 52 seconds for H (much less than the time constants involved). The σ was less than 2.3cm in the case of H and 7.6 in the case of Q_B .

Figures 9 and 10 show the responses of the manipulated variables in the same tests.

Figures 11 and 12 show some graphical results of response of Q_B and H to the disturbance of Q_B^{SP} . The maximum average SSE obtained was 0.91/h in the case of Q_B and 1.1cm in the case of H. The settling time of Q_B was less than 14seconds. The σ in the case of Q_B was less than 2.61/h and in the case of H less than 1.4cm.

Figures 13 and 14 show the manipulated variables changes.

6 Conclusions

This paper describes the work done in the evaluation of a fuzzy controller developed for the stabilization of a flotation column working with a mixture of water and air. The fuzzy controller is part of a system that works in real time. The study undertaken showed the adequate performance in load rejection and servo control of Collection Zone Height (H) and Bias Water Flowrate (Q_B) and it revealed also that fuzzy logic-based controller can be a solution for automatic control of column flotation.

One major advantage found in the development and application of fuzzy control is easily understandable by process engineers.

Controller tuning was the main difficulty encountered due to the multiple parameters involved becoming a time-consuming trial and error method.

The work was performed with a two phase mixture (air and water). More difficulties are expected in the application to the three phase system (water, air and solid particles). The need for an adaptative controller is anticipated as the means to cope with feed characteristics fluctuations.

References

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Fig. 3 - Response of H to a load disturbance (Q_F).



Fig. 6 - Response of $Q_{\rm W}$ to a load disturbance $(Q_{\rm F}).$



Fig. 4 - Response of $Q_{\scriptscriptstyle B}$ to a load disturbance $(Q_{\scriptscriptstyle F}).$



Fig. 5 - Response of $Q_{\scriptscriptstyle U}$ to a load disturbance $(Q_{\scriptscriptstyle F}).$



Fig. 7 - Response of H to a disturbance of H^{SP} .



Fig. 8 - Response of $Q_{\scriptscriptstyle B}$ to a disturbance of $H^{\scriptscriptstyle SP}\!.$



Fig. 9 - Response of $Q_{\scriptscriptstyle U}$ to a disturbance of $H^{\scriptscriptstyle SP}\!.$



Fig. 12 - Response of H to a disturbance of Q_B^{SP} .



Fig. 13 - Response of $Q_{\rm U}$ to a disturbance of $Q_{\rm B}^{SP}$.



Fig. 14 - Response of Q_{W} to a disturbance of Q_{B}^{SP} .



Fig. 10 - Response of Q_w to a disturbance of H^{sp} .



Fig. 11 - Response of $Q_{\scriptscriptstyle B}$ to a disturbance of $Q_{\scriptscriptstyle B}{}^{\scriptscriptstyle {\rm SP}}$